Performance of the MK-IX Explosive-Driven Flux-Compression Generator*

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Abstract

In the Seventh IEEE Pulsed Power Conference in Monterey, CA (1989), Fowler and others published the performance characteristics for the recently developed MK-IX Explosive-Driven Magnetic Flux-Compression Generator (FCG). Since that time we have used this generator in a variety of applications, and have published the results as one of the features of each individual experiment. In this paper, we collect the results from these applications to review the performance of the FCG. The application requiring the largest routine current delivery was the Los Alamos Procyon system. In that system, the MK-IX was the prime power supply and we worked at current levels of ~21.5 MA in 73 nH. We also used a MK-IX as a booster to supply initial flux for the CN-III generator, which generated a final current of ~160 MA. In Procyon applications, the generator operated with a combined system jitter of 6% over a seven shot series where the MK-IX load was nominally identical. We discuss these and other results, and note how the jitter would be reduced in future applications.

I. Introduction

The high explosive pulsed power (HEPP) team at Los Alamos has developed a wide range of high explosive (HE) driven FCG devices. In this paper we discuss the MK-IX, which is designed for multi-megajoule applications. The MK-IX operates near the parameters of a previous design, the MK-VIII[1], but at a considerably reduced cost. The MK-VIII was built to replicate the Russian C-320 FCG[2] from information available in the literature, and used materials not readily available in the US. In addition, the C-320 and MK-VIII FCGs have a tapered armature near the output end of the generator. This provides increased dL/dt near the end of the generator run, but considerably complicates HE and armature manufacture. The defining MK-IX publication was made in the 1989 IEEE Pulsed Power Conference by Fowler and Caird[3]. Since that time, we have used the MK-IX routinely, but published results have focused on the application and there has been no attention given to the MK-IX itself. In this paper we have collected information from experiments using the MK-IX to provide an overview of its performance in HEPP systems.

The 1980s and '90s were an active period for high energy HEPP research at Los Alamos. During that period, we developed and fielded the MK-VIII, MK-IX, a sweeping wave coaxial (coax) generator[4], and the CN-III generator[5], among others. We also developed three high energy systems for z-pinch implosion research, Laguna[6], Procyon[7], and Ranchero[8]. For the CN-III, the MK-IX served as a booster to supply initial flux to the high current generator. Ranchero experiments never required a booster, but the MK-IX can be used when higher current Ranchero experiments are called for[9]. For Laguna and Procyon, the MK-IX was the prime power supply in a system with an explosively formed fuse (EFF) opening switch as a power conditioner[10]. We will discuss the performance of the MK-IX in both applications, and focus on the Procyon system. Procyon consisted of a 12 shot series, of which eight had nominally identical feed and load configurations for the MK-IX.

There were two surprises in reviewing files that dated back to the mid eighties. It was disappointing to discover that we had given little attention to MK-IX performance in our data analysis. From the data readily available, we had few high quality initial current traces to consider for this paper. This precluded our normalizing generator performance to equivalent initial currents on Procyon tests, which otherwise was our best opportunity for good performance statistics. The best we are able to do is show the total scatter in peak current for the series. On the other hand, it is rewarding to discover how much we have improved in our techniques, both in terms of diagnostic accuracy and accuracy in hitting a desired initial field. We were proud of these systems at the time, and achieved many of our goals, but we would certainly field them with greater precision today. As a final note, we also discovered that much of our old digital data is on computer media that are perilously close to being no longer readable. We will convert these to a newer format, and it is possible that good quality initial current traces for Procyon tests will be found in those records.

II. The CN-III Generator Tests

The CNIII generator was designed to operate near FCG performance limits at very high current, and the generator was fired three times with increasing currents (68, 105, and 156 MA). Prior to the final test, the HE and armature diameters were increased because in the intermediate test it appeared that the kinetic energy of the armature was barely sufficient for complete flux compression. The design goal for the test was 160 MA,

0-7803-9189-6/05/$20.00

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Performance of the MK-IX Explosive-Driven Flux-Compression Generator***	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Los Alamos National Laboratory, Los Alamos, NM 87545**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

and while the permanent capacitor bank at our firing point could supply enough initial flux to produce over 100 MA with the CN-III, to reach the ultimate goal a MK-IX was used to supply the CN-III initial flux. The initial inductance of the CN-III on that test was 148 nH, including input cables, and the current from the MK-IX was 6.1 MA. The MK-IX was injected with a 260kA initial current from the capacitor bank, 3000 µF at 14.5 kV. The relevant MK-IX performance parameters are summarized in Table 1, along with the other experiments we investigated.

III. Laguna System Tests

The Laguna system was designed for powering plasma z-pinch experiments and the series consisted of 10 experiments. The initial conditions constituting the MK-IX load were changed more than once during the series, and it is not a good series to focus on. A number of interesting points about the MK-IX came out of this series, however, because the system was being developed shortly after the advent of the MK-IX design. In preparation for the Laguna series we established a practical working limit for flux loading into the MK-IX. Our firing point has four discrete 600 kJ capacitor bank modules which can be combined to provide initial flux for experiments. In an attempt to get the largest possible current into (and out of) the MK-IX for Laguna experiments, we used three modules of the bank. The resulting magnetic pressure profile stressed the MK-IX windings too much, however, and the generator failed before flux compression began[11]. We were unable to study the flux loading issue in detail, but instead adopted the practice of using a three-plate header to place two modules in series. This reduced the current from what was available from three modules, and it also shortened the time scale. When the first test in this configuration succeeded, we commenced characterization tests and subsequently Laguna tests using the technique.

During this period we also changed from Comp B HE to PBX-9501. Comp B was the best match for the HE used in the C-320, and was used in the MK-VIII and subsequently in the MK-IX. For increased performance, and reduced price as a bonus, we changed to PBX-9501. This gave us measurably smaller time integrated losses due to the faster, higher pressure HE.

The performance of the MK-IX during the Laguna series is summarized in Table 1. The Laguna tests are represented by the average over the last five tests of the series, which are nominally the same.

IV. Procyon System Tests

The Procyon system was the next step up from Laguna, and was successful in generating 1.7 MJ of soft x-rays[12]. The tests are the best we have for examining variations in MK-IX, because we conducted eight experiments in essentially identical configurations. (We tested four different plasma physics loads, but those changes did not affect the MK-IX). In addition, we developed a coaxial output section for Procyon, and it is likely that the carefully bolted coaxial load was more consistent than a cable connected load. Finally, the armature configuration at the end of flux compression was analyzed, and we knew how much inductance was left at that time. This should be very reproducible, and we were able to fold this information into our analysis. Figure 1 shows the Procyon layout.

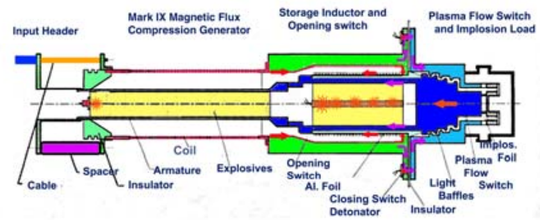

Figure 1 Procyon cross section

When we began writing this paper, we believed the most likely source for error in our tests was in the precision with which we reproduced the initial current in the MK-IX. Recent work has shown that initial current variations can be reduced by performing better bank voltage calibrations than we did in the past. Our plan was to first look at over-all system reproducibility, then examine the effect of normalizing the output current according to variations in the initial current. However, in going back to the old data, we discovered that high quality initial current data were not available in the files and our input current measurements are derived from less sensitive diagnostics with large uncertainty. As a result, we have used the average initial current already published[7] (465kA) for the analysis in Table 1, and the best synopsis we can present is the over-all peak current variation. Figure 2 shows current profiles from seven consecutive tests. This is a snapshot of the storage inductor current from about 2 µs before EFF first motion until about 2 µs after current transfer to the dynamic load is complete. The peak current from the MK-IX is seen just before EFF first motion, and the spread in this value over the tests is 1.3 MA, or about 6%. While we currently trust our Faraday rotation measurements to a per cent or two, the accuracy of both those and our Rogowsky coils at that time were in the neighborhood of 5%. As a result, much of the scatter seen in the data is likely due to our diagnostics. The eighth shot in this series must be regarded as a failure in terms of MK-IX performance. During the MK-IX flux compression phase of the experiment, there were obvious breakdowns within the generator, and the peak current was reduced from the values shown in the table by ~20%. Some experiments, including the one we were performing at the time, will yield data in such a case, but in critical applications, this

test would certainly have to be repeated. This failure was one of the 12 total Procyon tests and was the last of the eight tests with identical loads. It is also the only test among the 25 we looked back at that was noted as off normal in the records.

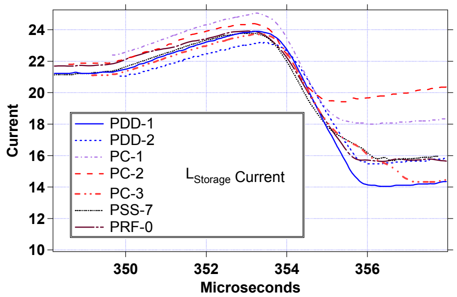

Figure 2 Storage inductor currents for seven consecutive Procyon experiments. The current from the MK-IX is that prior to the upward break just before 350 μs, and varies from 21.1 MA to 22.4 MA, a 6% spread. The standard deviation, σ_{IF}, is 0.46 MA or 2%.

V. Conclusions

We have examined records for 25 experiments on which MK-IX generators were used. Except for the characterization tests, we did not focus on the MK-IX performance at that time, and the quality of the information in the files is not as good as we would have liked. Of the 25 tests, only one Procyon test was noted to have experienced an internal failure, resulting in a 20% reduced peak current. The set of tests with the most consistent hardware was the Procyon series. We conducted eight of these tests in nominally identical configurations. Unfortunately, we do not have good initial current data and cannot scale results by that number. Rather, we can only show the total system jitter over these tests, including initial current variations, diagnostics uncertainty, and actual generator variation. The total spread in this series was 6%, with a standard deviation of 0.468 MA (~2%). The failed generator was one of the eight tests, and is not included in these statistics. With modern diagnostics and bank calibration techniques, we feel we can improve somewhat on that performance. The table gives actual gain divided by theoretical gain as a figure of merit for generator performance. Different cable configurations are not taken into account in this calculation. Procyon, with no cables, has the highest efficiency, even though it operated near the top of the performance range. The 30 MA characterization test had the worst, at 32%, and one assumes that is due to it operation at the highest peak current (~0.75 MA/cm of wire diameter). Laguna had the longest cables, and is the worst efficiency of the relatively low current applications. Clearly, minimizing the resistance in connecting the generator to its load is very important to peak generator performance. In future work we will focus on eliminating manufacturing flaws that could lead to the one failed shot among 25, and on maintaining the manufacturing standards. Making a production run, rather than fabricating each as a prototype, should also help consistency. However in considering the 2% standard deviation for Procyon, and 4% for Laguna, we feel that a significant part of the jitter seen in those tests is due to variations in diagnostics, or otherwise external to the generator, and fielding experiments with current techniques will naturally tighten up the performance.

Finally, we expect that there is some technique for increasing the initial current into the MK-IX beyond the 465 kA-480 kA available from the two module Marx configuration we have used. A booster generator that will deliver larger current and have a smaller effective risetime, for instance, could serve the purpose and if the need arises, we hope to be able to explore that issue.

Experiment	L_{Load}(nH)	G_{TH}	G_{ACT}	I_0(kA)	I_f(MA)	G_{ACT}/G_{TH}	σ_{IF}(MA)
MK-IX Characterization 2	56.4	128	56.9	413	23.5	0.44	
MK-IX Characterization 3	35	206	65.2	470	30	0.32	
CN-III	148	49.7	23.46	260	6.1	0.47	
Laguna series*	140	52	21.7	480	10.2	0.41	0.38
Procyon series	73**	101	49.65	465**	21.5	0.49	0.46

Table 1. Summary of MK-IX results. MK-IX characterization 1 and 2 are from ref. 3. I_0 is the initial current in the MK-IX. G_{TH} is the ideal FCG gain given by the ratio of initial to final circuit inductance. G_{ACT} is the actual gain, given by the ratio of final to initial current. σ_{IF} is the standard deviation of the distribution of I_f values. * Laguna I_f values are normalized to an initial current of 480 kA. ** From ref. 7. Procyon final currents could not be normalized, due to lack of accurate I_0 values currently available.

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* This work supported by the US DOE